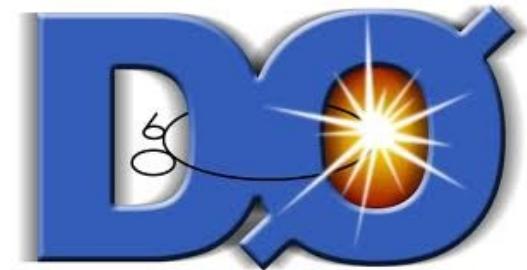


# *Measurements of Top Quark Production and Properties at the Tevatron*

*Pavol Bartoš*

*(Comenius University)*

*On behalf of CDF and D0 collaborations*



*Moriond QCD, March 22-29, 2014*

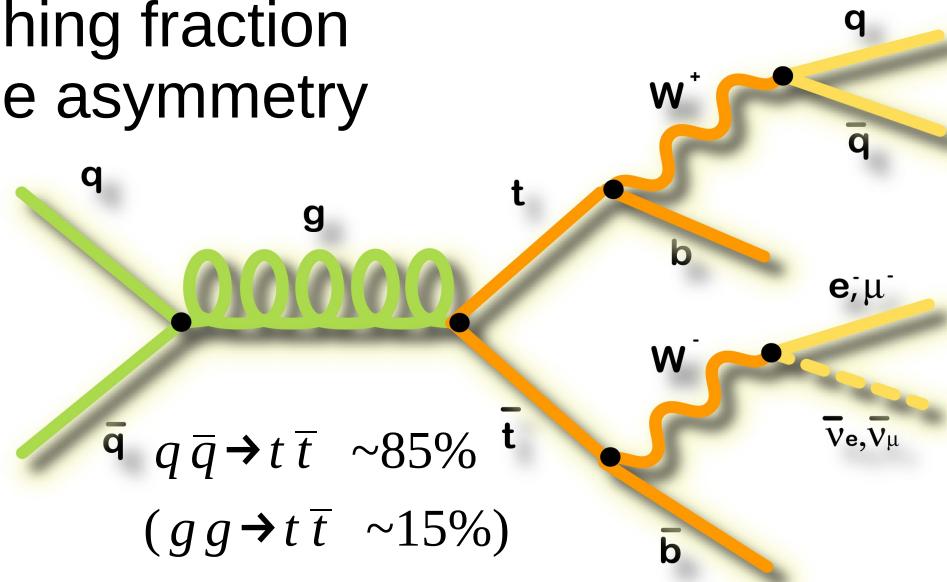
# Outline

## → Top quark production

→ differential and inclusive cross-section of  $t\bar{t}$  production

## → Top quark properties

- decay width
- branching fraction
- charge asymmetry

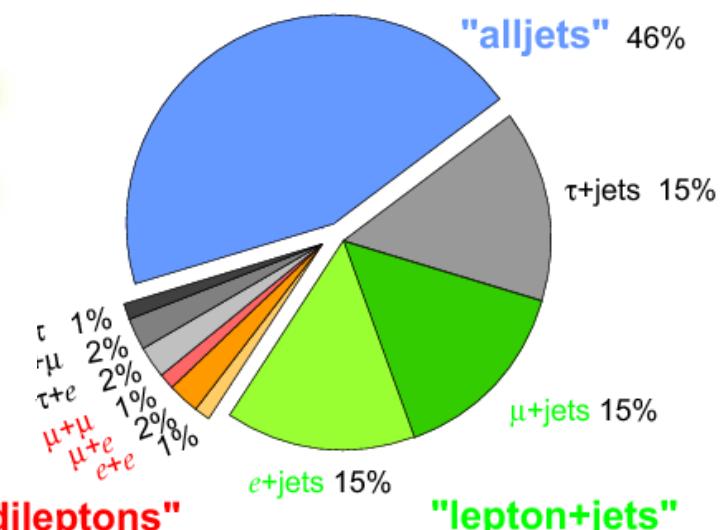


## → Not included

- top quark mass (Sung Woo Youn)
- single top production (Matteo Cremonesi)

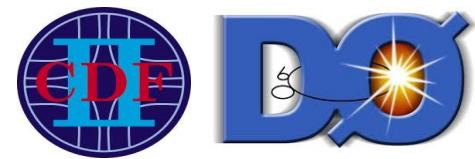
According to SM:  
 $B(t \rightarrow Wb) \sim 100\%$

Top Pair Branching Fractions



# $t\bar{t}$ cross sections

# Inclusive $t\bar{t}$ cross section



Tevatron Run II

	$\overline{p}p \rightarrow t\bar{t}$ cross section (pb)	$\sqrt{s} = 1.96$ TeV
CDF dilepton	$7.09 \pm 0.83$ $\pm 0.49 \pm 0.67$	$8.8 \text{ fb}^{-1}$
CDF ANN lepton+jets	$7.82 \pm 0.56$ $\pm 0.38 \pm 0.41$	$4.6 \text{ fb}^{-1}$
CDF SVX lepton+jets	$7.32 \pm 0.71$ $\pm 0.36 \pm 0.61$	$4.6 \text{ fb}^{-1}$
CDF all-jets	$7.21 \pm 1.28$ $\pm 0.50 \pm 1.18$	$2.9 \text{ fb}^{-1}$
CDF combined	$7.63 \pm 0.50$ $\pm 0.31 \pm 0.39$	
D0 dilepton	$7.36 \pm 0.85$	$5.4 \text{ fb}^{-1}$
D0 lepton+jets	$7.90 \pm 0.74$	$5.3 \text{ fb}^{-1}$
D0 combined	$7.56 \pm 0.59$ $\pm 0.20 \pm 0.56$	
<b>Tevatron combined</b> $m_t = 172.5 \text{ GeV}$	$7.60 \pm 0.41$ $\pm 0.20 \pm 0.36$	

$\overline{p}p \rightarrow t\bar{t}$  cross section (pb) at  $\sqrt{s}=1.96$  TeV

→ Tevatron combination

(BLUE method)

- 2 D0 measurements
- weight of 40%
- 4 CDF measurements
- weight of 60 %
- systematic is dominated by signal modeling

arXiv:1309.7570, accepted by PRD

$$\sigma_{t\bar{t}} = (7.60 \pm 0.41) \text{ pb}$$

$$\chi^2 = 0.01 / 1; \text{ Prob } 92\%$$

SM prediction (NNLO+NNLL):  
arXiv:1303.6254

$$\sigma_{t\bar{t}} = 7.35^{+0.11}_{-0.21} (\text{scales})^{+0.17}_{-0.12} (\text{PDF})$$

(using  $M_t = 172.5 \text{ GeV}$ )

# Differential $t\bar{t}$ cross sections (I)

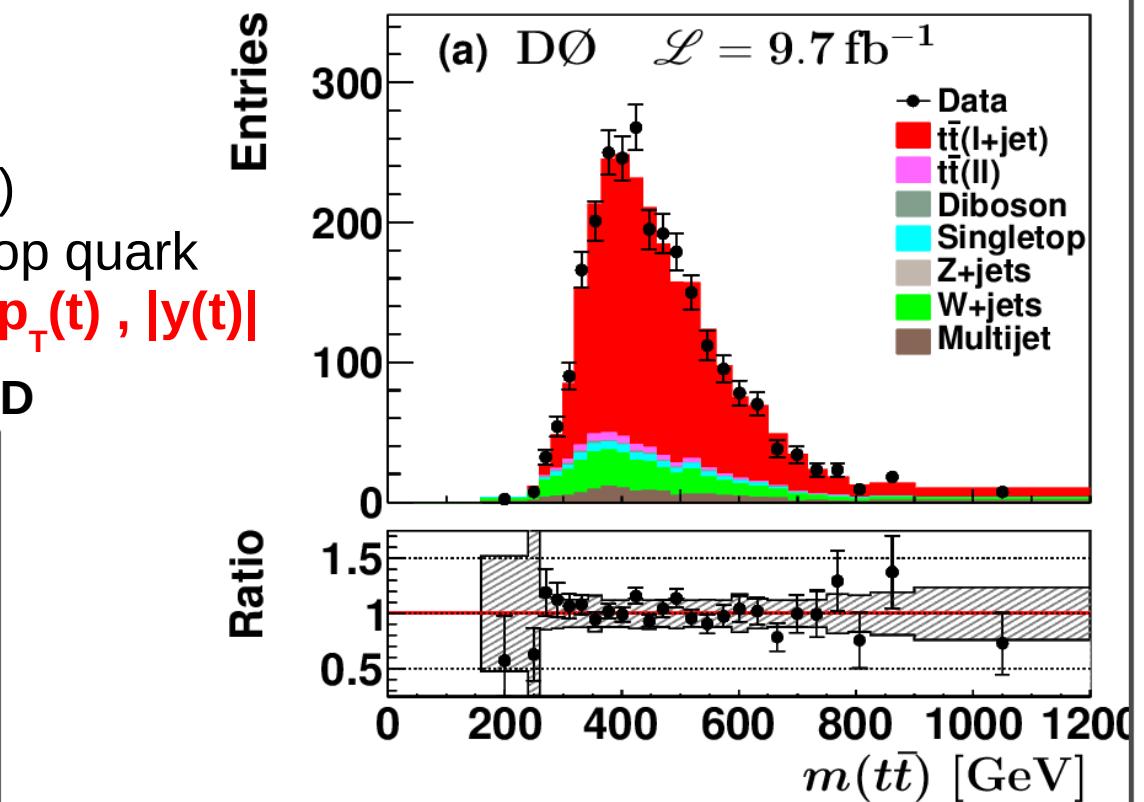
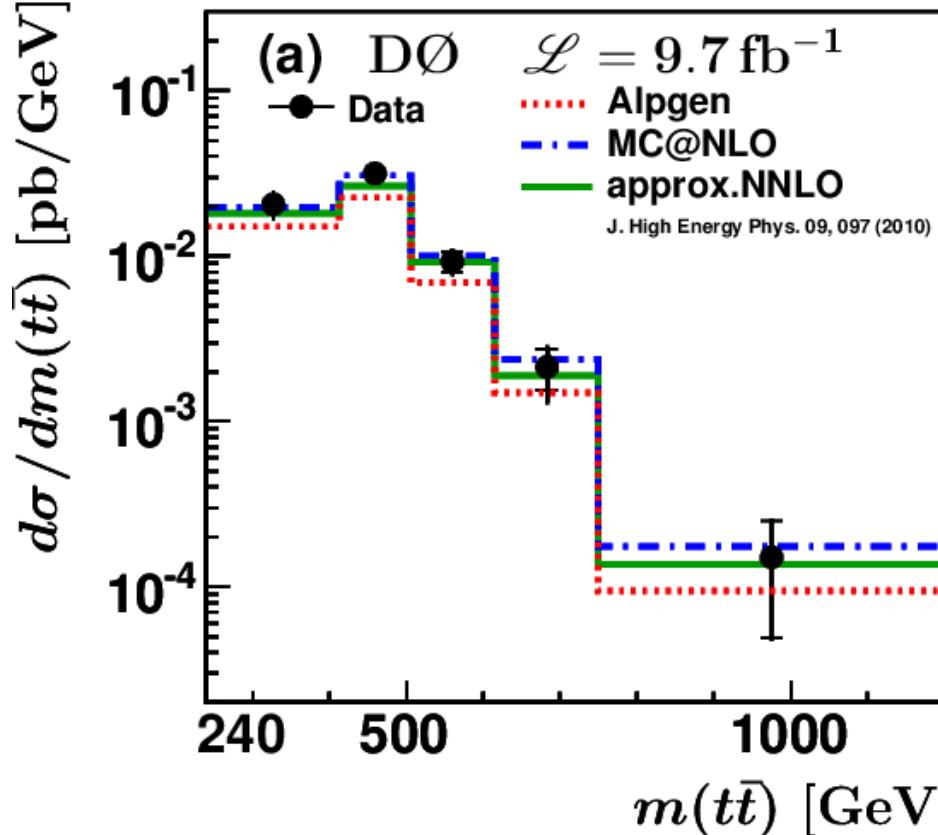


- provides direct test of QCD, constraints on axigluon models
- important for QCD modeling (searches for new physics)

## → *$\ell$ +jet channel with 1 b-tag*

- final state is obtained by kinematic reconstruction ( $\chi^2$ -based method)
- result is corrected to parton-level top quark
- cross section as a function of  $m_{t\bar{t}}$ ,  $p_T(t)$ ,  $|y(t)|$

arXiv:1401.5785, submitted to PRD



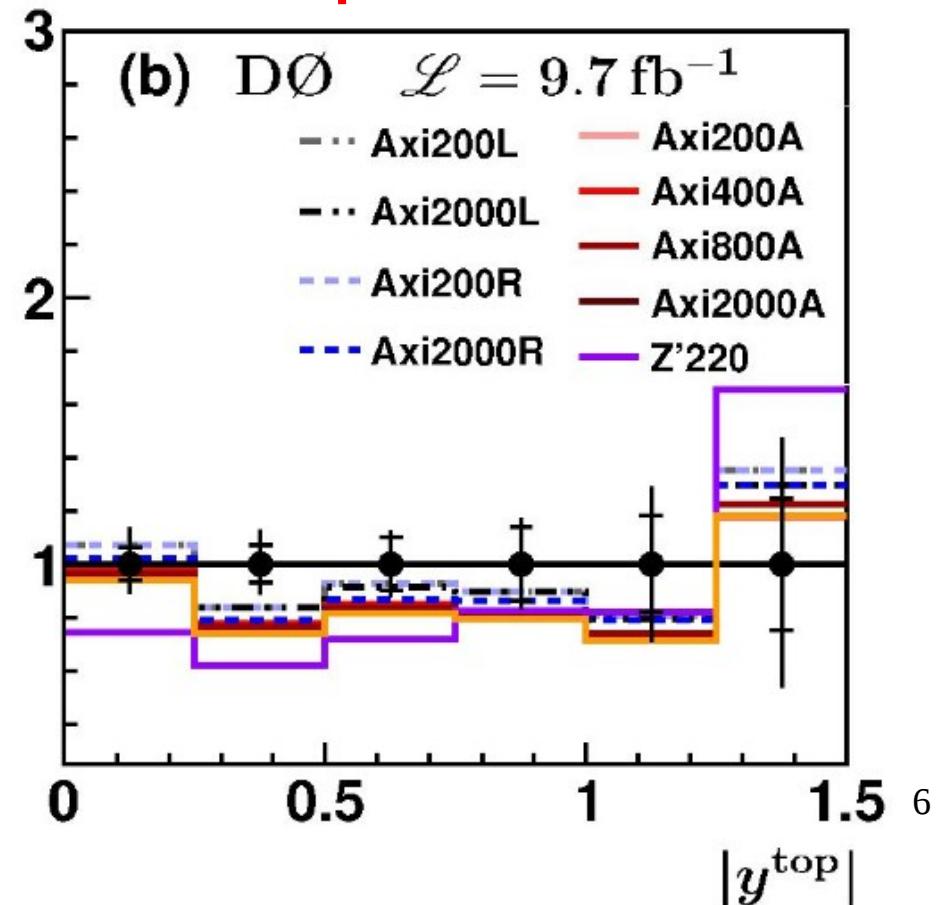
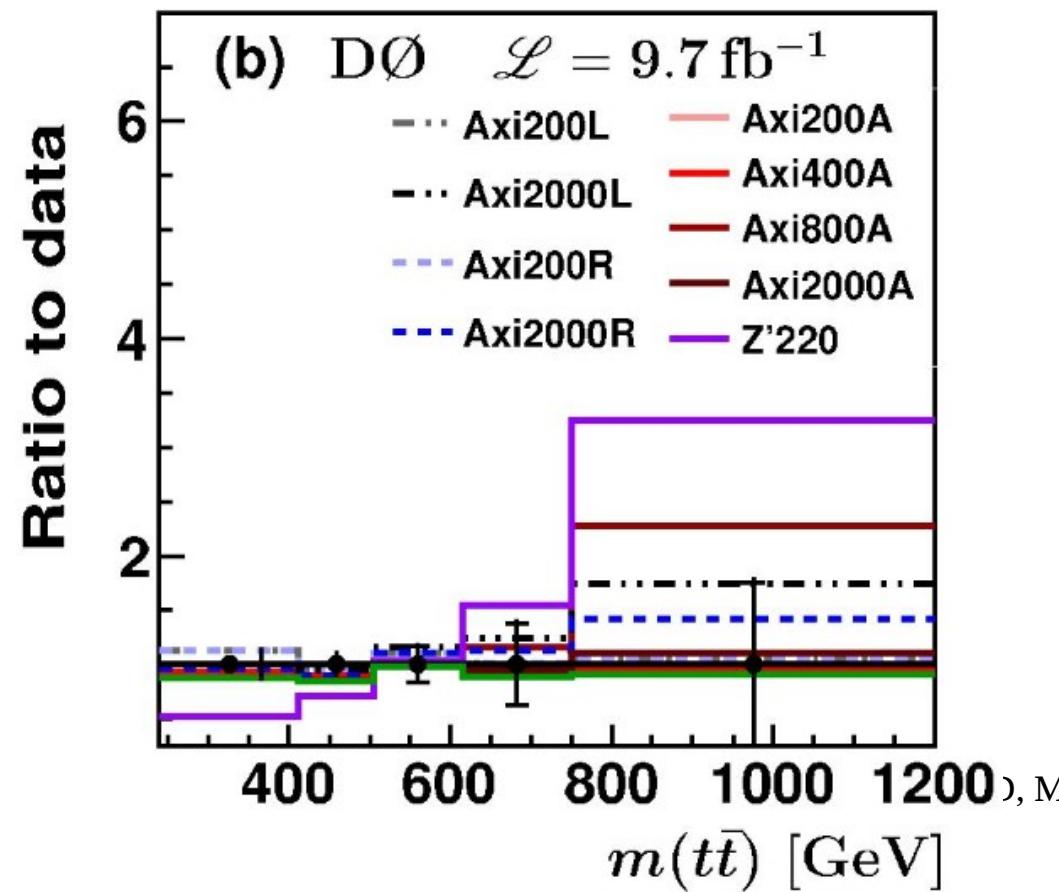
- measured with typical **precision ~9%**
- main systematic source: signal modeling
- **general agreement with predictions** by QCD generators & approximate NNLO

# Differential $t\bar{t}$ cross sections (II)



- Different axigluon models with different couplings (used in asymmetry studies)  
differential cross section predictions provided by A. Falkowski (et al)  
arXiv 1401.2443
- in these models, forward-backward asymmetry will be increased, but also  
the **differential cross section distributions will be changed**
- high-mass axigluons highly constrained by LHC measurements, while  
low masses not so much (but the effects are small)

**Some models are in tension with the presented data !**



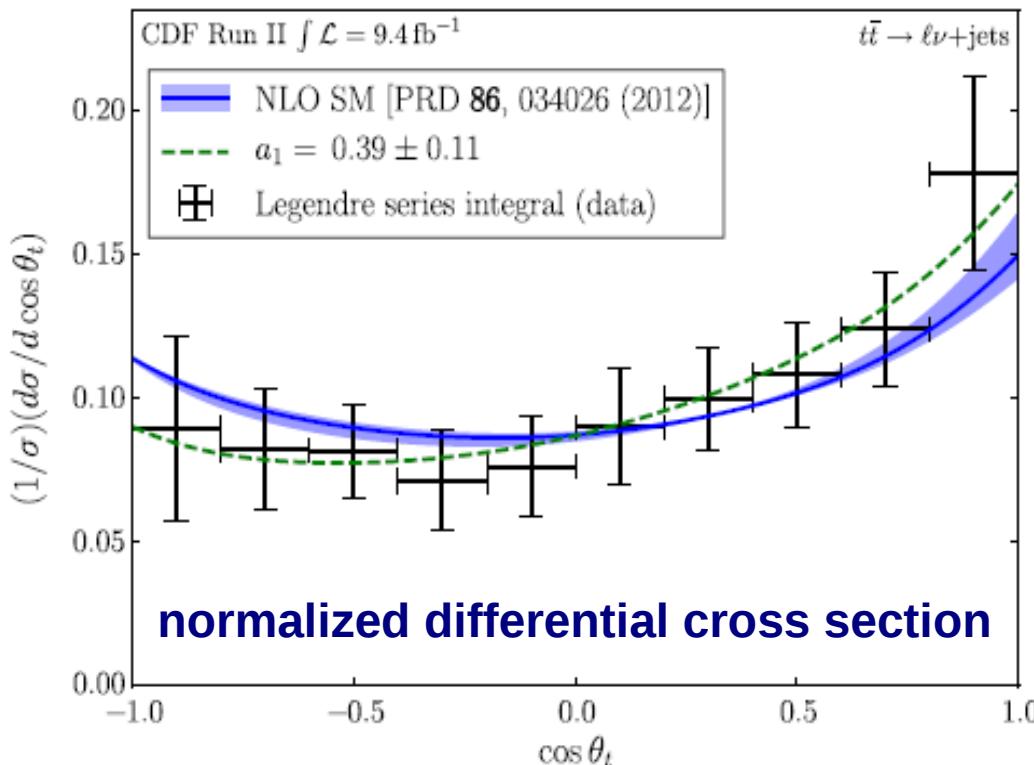
# Differential $t\bar{t}$ cross sections

- employ Legendre polynomials to characterize the shape of differential cross section:

$$\frac{d\sigma}{d(\cos\theta_t)} = \sum_{\ell=0}^{\infty} a_{\ell} P_{\ell}(\cos\theta_t),$$

$\theta_t$  is angle between top-quark momentum and the incoming proton momentum in  $t\bar{t}$  center-of-mass frame

- full shape has potential to discriminate among various calculations of SM and non-SM physics models
- moment  $a_0$  contains only total cross section, we scale all moments, ( $a_{\ell}$ ), so that  $a_0 = 1$ .



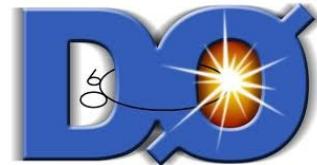
$\ell$	$a_{\ell}$ (obs)	$a_{\ell}$ (pred)
1	$0.40 \pm 0.12$	$0.15^{+0.07}_{-0.03}$
2	$0.44 \pm 0.25$	$0.28^{+0.05}_{-0.03}$
3	$0.11 \pm 0.21$	$0.030^{+0.014}_{-0.007}$
4	$0.22 \pm 0.28$	$0.035^{+0.016}_{-0.008}$
5	$0.11 \pm 0.33$	$0.005^{+0.002}_{-0.001}$
6	$0.24 \pm 0.40$	$0.006^{+0.002}_{-0.003}$
7	$-0.15 \pm 0.48$	$-0.003^{+0.001}_{-0.001}$
8	$0.16 \pm 0.65$	$-0.0019^{+0.0003}_{-0.0003}$

$a_1 = 0.40 \pm 0.12$   
PRL 111 182002 (2013)

*Decay width  
&  
branching fractions*



# Top quark width



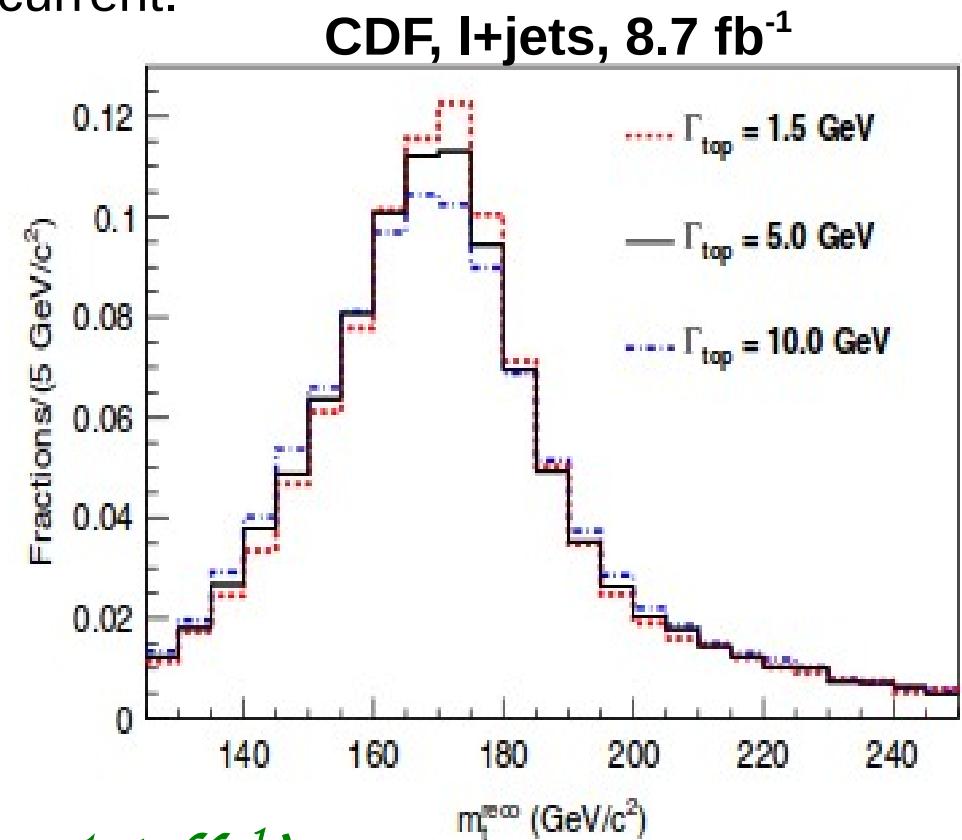
- largest decay width of the known fermions
- deviation from SM could indicate decays via e.g., charged Higgs boson, stop squark, or flavor changing neutral current.

## → CDF direct measurement

- data fitted by the MC templates
- $\Gamma_t$  extracted from width of  $m_t^{reco}$

$$\Gamma_t = 2.21^{+1.84}_{-1.11} \text{ GeV}$$

PRD 111, 202001 (2013)



## → D0 indirect measurement ( $l+jets, 5.4 \text{ fb}^{-1}$ )

- using  $\sigma(t\text{-channel})$  to extract partial top width and  $B(t \rightarrow Wb)$  to get total width

$$\Gamma_t = 2.00^{+0.47}_{-0.43} \text{ GeV}$$

PRD 85, 091104 (2012)



# Branching fractions



→ using the measurement  $V_{tb}$  can be extracted

→ deviation from expected value could imply existence of extra generation of quarks

## → *CDF measurement*

→ divide sample into bins by lepton flavour and number of b-tagged jets

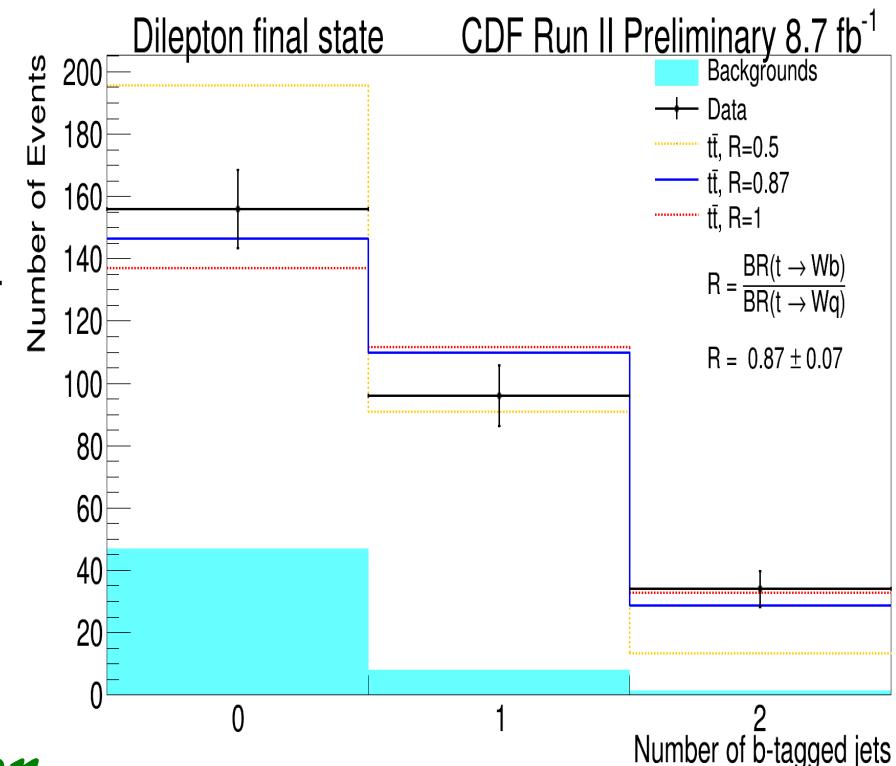
→ using likelihood fit with R as free parameter

$$R = 0.87 \pm 0.07 \text{ (stat+syst)}$$

$$|V_{tb}| = 0.93 \pm 0.04 \text{ (stat+syst)}$$

CDF note 11048

$$R = \frac{\mathcal{B}(t \rightarrow Wb)}{\mathcal{B}(t \rightarrow Wq)} = \frac{|V_{tb}|^2}{|V_{tb}|^2 + |V_{ts}|^2 + |V_{td}|^2}$$



## → *D0 – l+jets & dilepton combination*

→ fit R and the  $t\bar{t}$  cross section together

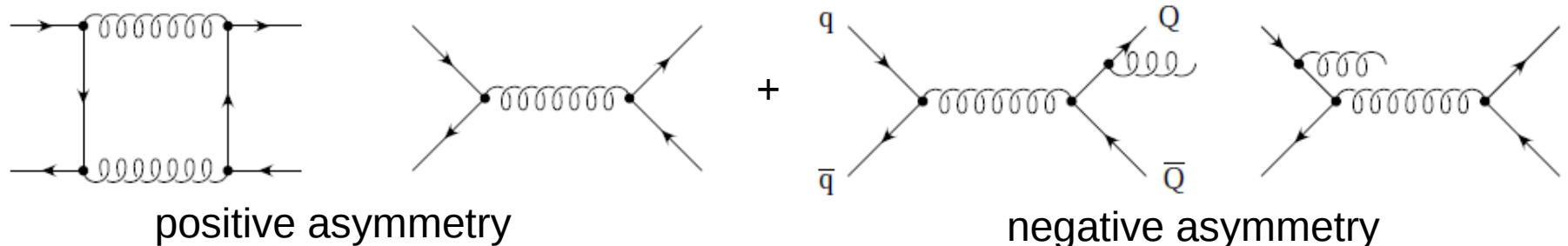
$$R = 0.90 \pm 0.04 \text{ (stat+syst)}$$

PRL 107, 121802 (2011)

# *Production asymmetries*

# $t\bar{t}$ forward-backward asymmetry

- at NLO, the SM predicts asymmetry in  $t\bar{t}$  production
    - asymmetry comes from events with  $q\bar{q}$  initial states,  $gg$  is symmetric



- ## → **Definition:**

$$A_{\text{FB}} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)} \quad , \text{ where } \Delta y = y_t - y_{\bar{t}}$$

- ## → **Methodology:**

- using l+jet events (full statistics)
  - **full kinematic reconstruction** of  $t\bar{t}$  final state
    - CDF:  $\chi^2$ -based fit
    - D0: new kinematic fit algorithm for events with  $\geq 4$  jets  
 $m_{t\bar{t}}$  obtained from multivariate regression combining 3 algorithms
  - **correction for parton level** – using regularized unfolding in 2D
  - inclusive asymmetry expressed also **as function of:**  $m_{t\bar{t}}$  – CDF, DO



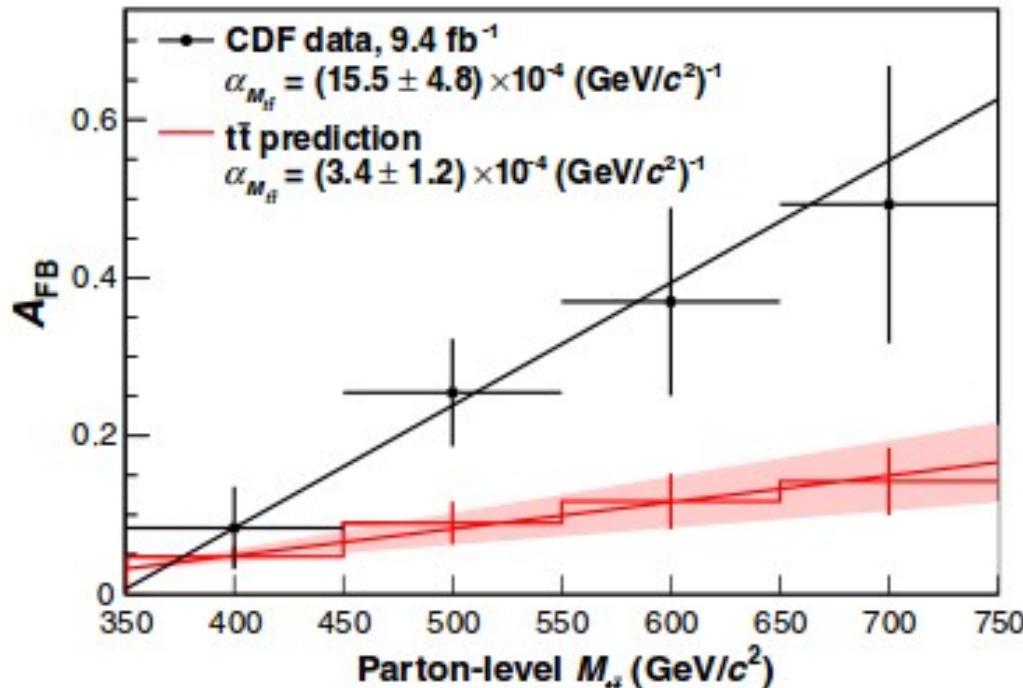
# $t\bar{t}$ forward-backward asymmetry



→ CDF Results:

$$A_{FB} = 0.164 \pm 0.039 \text{ (stat.)} \pm 0.026 \text{ (syst.)}$$

PRD 87, 092002 (2013)



Slopes different w.r.t. SM predictions:

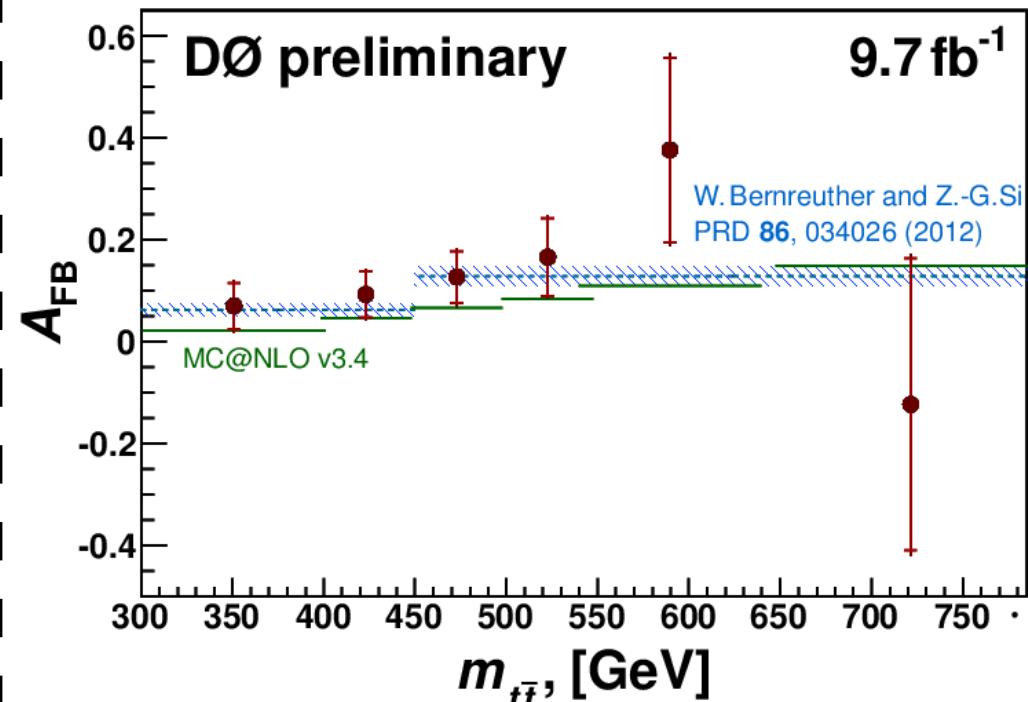
$2.4\sigma$  ( $M_{tt}^2$ ),  $2.8\sigma$  ( $|\Delta y|$ )

From differential cross section **result** (PRL 111 182002 (2013) and slide 7):  
**favors the asymmetry models with strong s-channel components**

→ D0 results

$$A_{FB} = 0.106 \pm 0.027 \text{ (stat.)} \pm 0.013 \text{ (syst.)}$$

D0 Conf note 6425



**Compatible** with SM predictions  
and with CDF result

# *Lepton based asymmetry*

- **Advantage:** no need to reconstruct the  $t\bar{t}$  final state.  
sensitive to top quark polarization
- lepton direction is measured with high precision + good charge determination

- **Definition:**

**Dilepton events:**  $\Delta\eta = \eta_{l^+} - \eta_{l^-}$

$$A_{FB}^\ell = \frac{N(qy_\ell > 0) - N(qy_\ell < 0)}{N(qy_\ell > 0) + N(qy_\ell < 0)}.$$

$$A_{FB}^{\Delta\eta} = \frac{N(\Delta\eta > 0) - N(\Delta\eta < 0)}{N(\Delta\eta > 0) + N(\Delta\eta < 0)}$$

- **CDF methodology: (same for l+jets and dilepton events)**

- asymmetry is decomposed into symmetric and asymmetric parts:

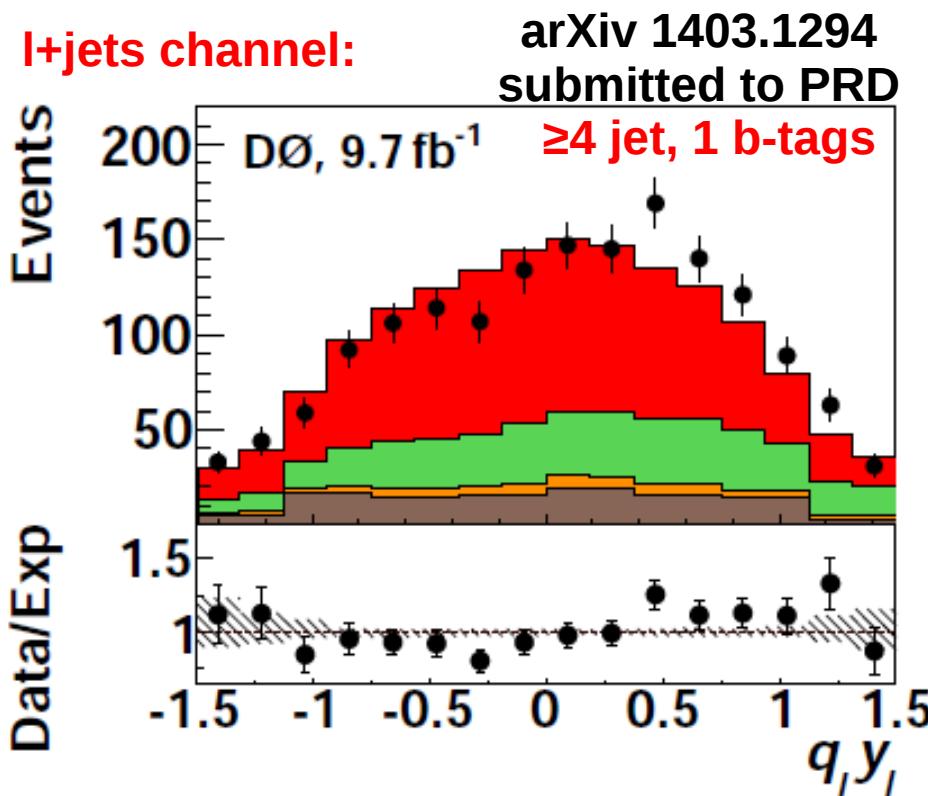
$$S(qy_\ell) = \frac{\mathcal{N}(qy_\ell) + \mathcal{N}(-qy_\ell)}{2} \quad \mathcal{A}(qy_\ell) = \frac{\mathcal{N}(qy_\ell) - \mathcal{N}(-qy_\ell)}{\mathcal{N}(qy_\ell) + \mathcal{N}(-qy_\ell)},$$

- symmetric part (obtained from MC) – largely insensitive to physics model
- asymmetric part is parametrized:  
$$\mathcal{A}(\bar{qy}_\ell) = a \tanh\left(\frac{qy_\ell}{2}\right)$$
- fit of asymmetric part allows to extrapolate to unmeasured region

# *Lepton based asymmetry*

## → D0 methodology: (l+jets events)

- using l + 3 jets in addition to l + ≥4 jets – increase statistics twice
  - l+3 jets has lower S/B ratio, helps to reduce acceptance corrections
- improve modeling of  $A_{FB}^l$  in W+jets using control region (3 jets+0 btag)
- asymmetry and sample composition is extracted by likelihood fit
- unfold for acceptance effects, study dependence on lepton  $p_T$  and  $y_l$



- D0 methodology: (dilepton events)
- background subtraction,
  - correction for selection effects
  - extrapolation to the full range of  $\eta$

, March 22-29, 2014

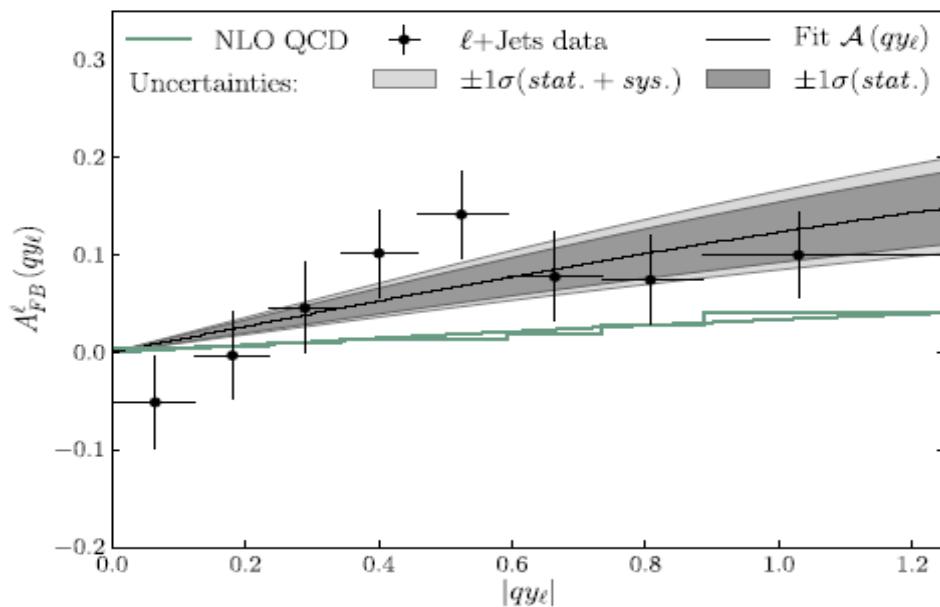
# Single-lepton asymmetry results

## $\ell + \text{jets}$ channel

CDF:

PRD 88, 072003 (2013)

$$A_{FB}^l = 0.094 \pm 0.024 \text{ (stat.)}^{+0.022}_{-0.017} \text{ (syst.)}$$



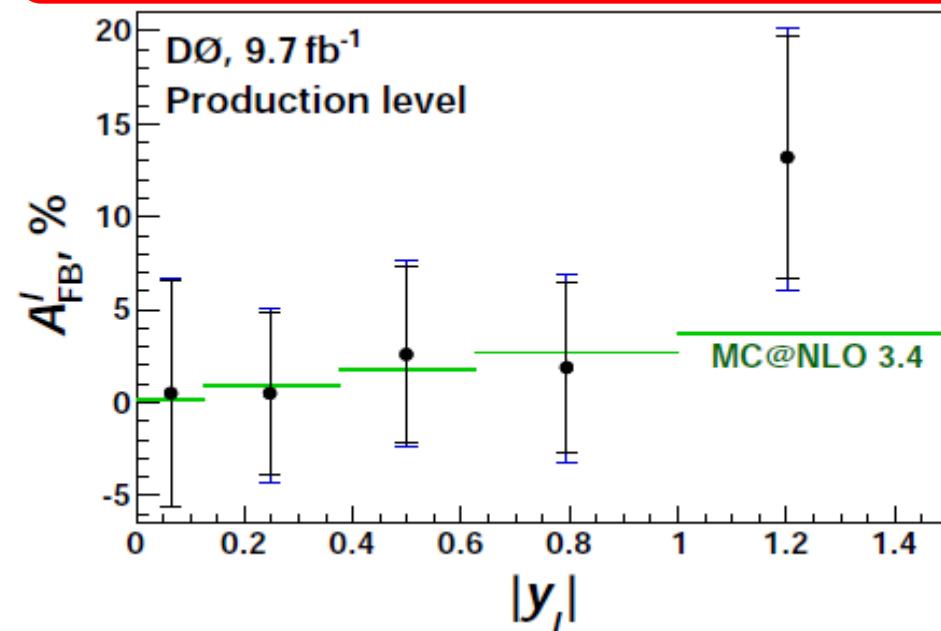
SM predicts:

$$A_{FB}^l = 0.038 \pm 0.003$$

D0:  $|y_\ell| < 1.5$ :

arXiv 1403.1294  
submitted to PRD

$$A_{FB}^l = 0.042 \pm 0.023 \text{ (stat.)}^{+0.017}_{-0.020} \text{ (syst.)}$$



MC@NLO  $|y_\ell| < 1.5$ :

$$A_{FB}^l = 0.020$$



# Single lepton asymmetry Dilepton channel



**SM predicts:**

$$A_{FB}^l = 0.038 \pm 0.003$$

**CDF:**

CDF note 11035

$$A_{FB}^l = 0.072 \pm 0.052 \text{ (stat.)} \pm 0.030 \text{ (syst.)}$$

**D0:**

PRD 88, 112002 (2013)

$$A_{FB}^l = 0.044 \pm 0.037 \text{ (stat.)} \pm 0.011 \text{ (syst.)}$$

---

**Combination ( $l+jet$ , dilepton)**

→ using BLUE method

**CDF:**

$$A_{FB}^l = 0.090^{+0.028}_{-0.026}$$

CDF note 11035

**2 $\sigma$  larger than the SM prediction**

**SM predicts:**

$$A_{FB}^l = 0.038 \pm 0.003$$

**D0:**

arXiv 1403.1294,  
submitted to PRD

$$A_{FB}^l = 0.047 \pm 0.023 \text{ (stat)} \pm 0.015 \text{ (syst)}$$



# Dilepton asymmetry



## Dilepton channel

CDF:

$$A_{FB}^{\Delta\eta} = 0.072 \pm 0.081$$

CDF note 11035

D0:

PRD 88, 112002 (2013)

$$A_{FB}^{\Delta\eta} = 0.123 \pm 0.054 \text{ (stat.)} \pm 0.015 \text{ (syst.)}$$

SM predicts:

$$A_{FB}^{\Delta\eta} = 0.048 \pm 0.004$$

D0:

PRD 88, 112002 (2013)

$$A_{FB}^l / A_{FB}^{\Delta\eta} = 0.36 \pm 0.20$$

SM (NLO):  $0.79 \pm 0.10$

2 $\sigma$  difference

## *Conclusions*

- the measurements are mostly in agreement with SM prediction
- CDF see higher production asymmetry in both  $t\bar{t}$  inclusive and lepton-based measurements
- D0 data compatible with SM prediction and also with CDF results
- For more Tevatron top quark results, please see Matteo Cremonesi's talk on single top (after coffee break)

## *Plans*

- Tevatron combination of production asymmetry results is on the table
- finalize other analysis using full data-set (spin correlation, mass,...)

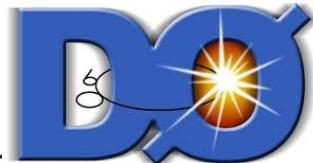
*Thank you!*

# *Backup slides*

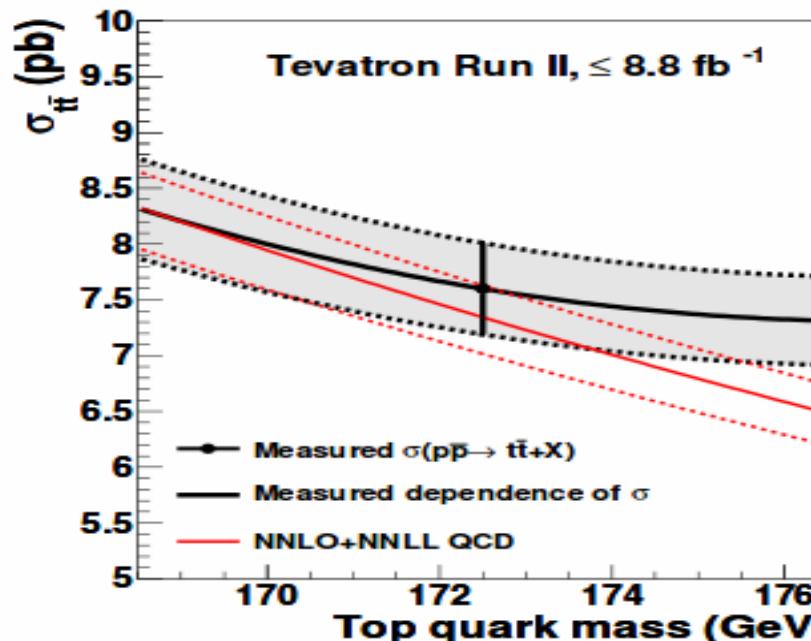


# Inclusive $t\bar{t}$ cross section

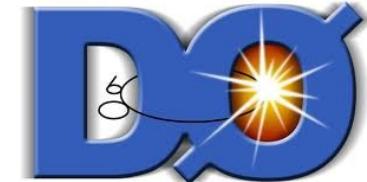
arXiv:1309.7570, accepted by PRD



	DIL	LJ-ANN	LJ-SVX	HAD	CDF combined
Central value of $\sigma_{t\bar{t}}$	7.09	7.82	7.32	7.21	7.63
Sources of systematic uncertainty					
Modeling of the detector	0.39	0.11	0.34	0.41	0.17
Modeling of signal	0.23	0.23	0.23	0.44	0.21
Modeling of jets	0.23	0.23	0.29	0.71	0.21
Method of extracting $\sigma_{t\bar{t}}$	0.00	0.01	0.01	0.08	0.01
Background modeled from theory	0.01	0.13	0.29	–	0.10
Background based on data	0.15	0.07	0.11	0.59	0.08
Normalization of $Z/\gamma^*$ prediction	–	0.16	0.15	–	0.13
Luminosity: inelastic $p\bar{p}$ cross section	0.28	–	–	0.29	0.05
Luminosity: detector	0.30	0.02	0.02	0.30	0.06
Total systematic uncertainty	0.67	0.41	0.61	1.18	0.39
Statistical uncertainty	0.49	0.38	0.36	0.50	0.31
Total uncertainty	0.83	0.56	0.71	1.28	0.50

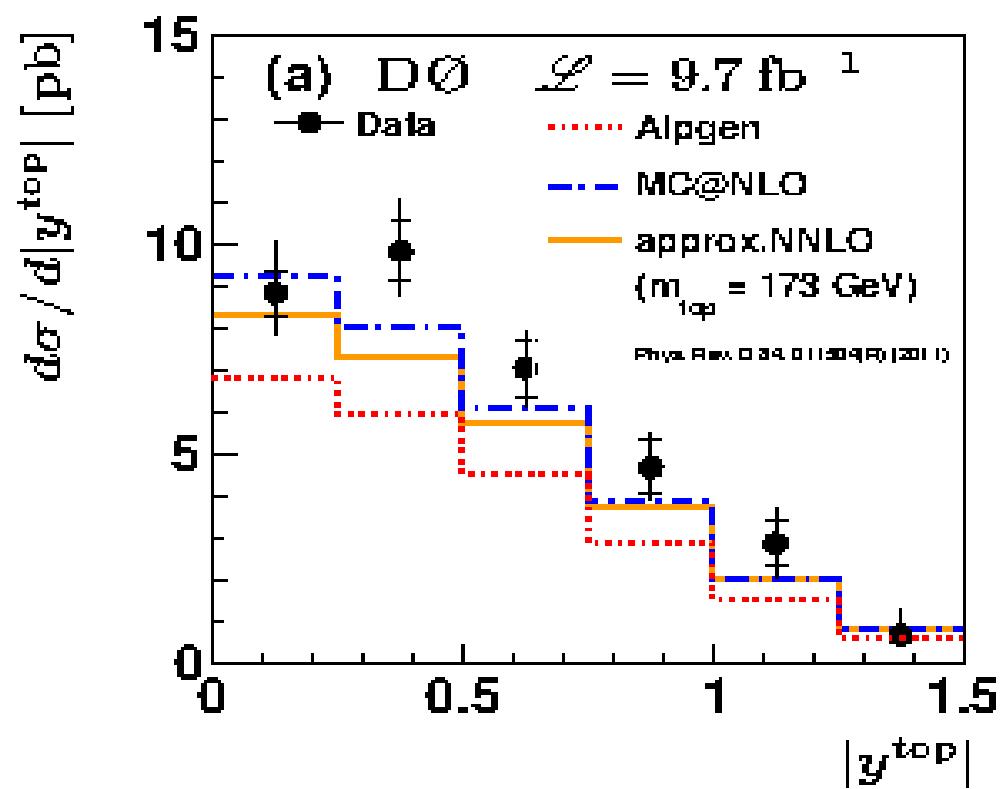
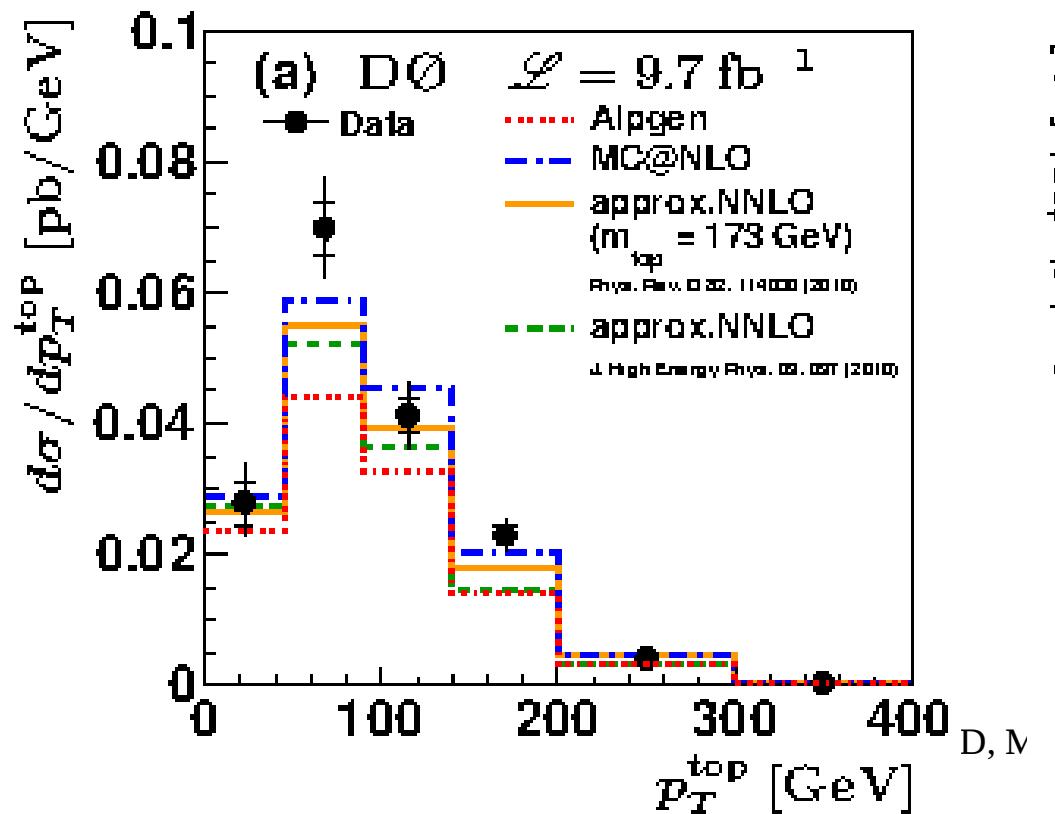


# Differential $t\bar{t}$ cross sections (I)

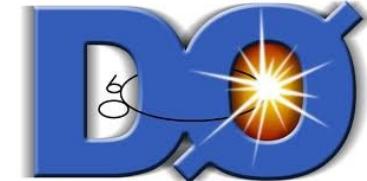


arXiv:1401.5785  
submitted to PRD

Source of uncertainty	Uncertainties, %	
	$\delta_{\text{incl}}$	$ \delta_{\text{diff}} $
Signal modeling	+5.2 -4.4	4.0 – 14.2
PDF	+3.0 -3.4	0.9 – 4.4
Detector Modeling	+4.0 -4.1	3.1 – 13.7
Sample composition	$\pm 1.8$	2.8 – 9.2
Regularization strength	$\pm 0.2$	0.8 – 2.1
Integrated luminosity	$\pm 6.1$	6.1 – 6.1
Total systematic uncertainty	+9.6 -9.3	8.5 – 23.1



# Differential $t\bar{t}$ cross sections (II)



ArXiv:1401.5785, submitted to PRD

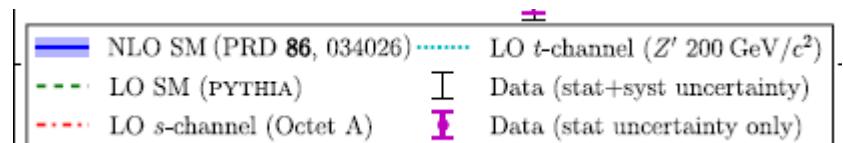
	$\sigma_{\text{tot}}(p\bar{p} \rightarrow t\bar{t})$ [pb]	$M(t\bar{t})$ [ $\chi^2/ndf$ ]	$ y^{\text{top}} $ [ $\chi^2/ndf$ ]	$p_T^{\text{top}}$ [ $\chi^2/ndf$ ]
Data	$8.27^{+0.92}_{-0.91}$ (stat. + syst.)	n.a.	n.a.	n.a.
pQCD NNLO	$7.24^{+0.23}_{-0.27}$ (scales + pdf)	0.98	3.71	4.05
non-SM model	$\Delta\sigma_{\text{tot}}(p\bar{p} \rightarrow t\bar{t})$ [pb]	$M(t\bar{t})$ [ $\chi^2/ndf$ ]	$ y^{\text{top}} $ [ $\chi^2/ndf$ ]	$p_T^{\text{top}}$ [ $\chi^2/ndf$ ]
$G'(l)$ , $m = 0.2$ TeV	$+0.97 \pm 0.06$ (scales)	0.96	1.07	1.20
$G'(r)$ , $m = 0.2$ TeV	$+0.97 \pm 0.06$ (scales)	0.96	1.07	1.20
$G'(a)$ , $m = 0.2$ TeV	$+0.06 \pm 0.04$ (scales)	0.85	3.55	3.88
$G'(a)$ , $m = 0.4$ TeV	$+0.26 \pm 0.04$ (scales)	0.44	2.65	3.26
$G'(a)$ , $m = 0.8$ TeV	$+0.22 \pm 0.04$ (scales)	0.97	2.86	3.23
$G'(l)$ , $m = 2.0$ TeV	$+0.87 \pm 0.15$ (scales)	0.58	1.27	3.78
$G'(r)$ , $m = 2.0$ TeV	$+0.55 \pm 0.06$ (scales)	0.43	1.94	2.75
$G'(a)$ , $m = 2.0$ TeV	$+0.05 \pm 0.06$ (scales)	0.88	3.56	4.11
$Z'$ , $m = 0.22$ TeV	$-1.00 \pm 0.06$ (scales)	4.95	8.27	7.48

Table of  $\chi^2/ndf$  values for data versus approximate pQCD at NNLO and the various axi gluon models and one  $Z'$  model. The masses of the new mediators are indicated together with the nature of the couplings ( $l$  left,  $r$  right and  $a$  axial couplings) in the first column (more details are given in Ref. [arXiv:hep-ph/1401.2443]).

# $t\bar{t}$ forward-backward asymmetry

Slopes different w.r.t. SM predictions:  
**2.8 $\sigma$  for  $|\Delta y|$  distribution**

PRL 111 182002 (2013)



PRD 87. 092002 (2013)

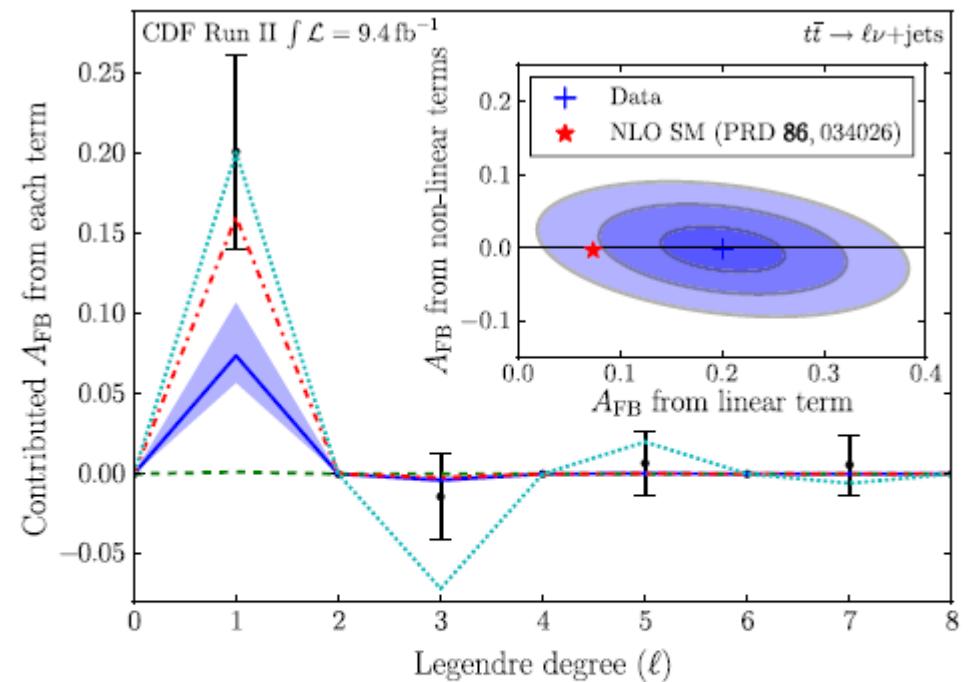
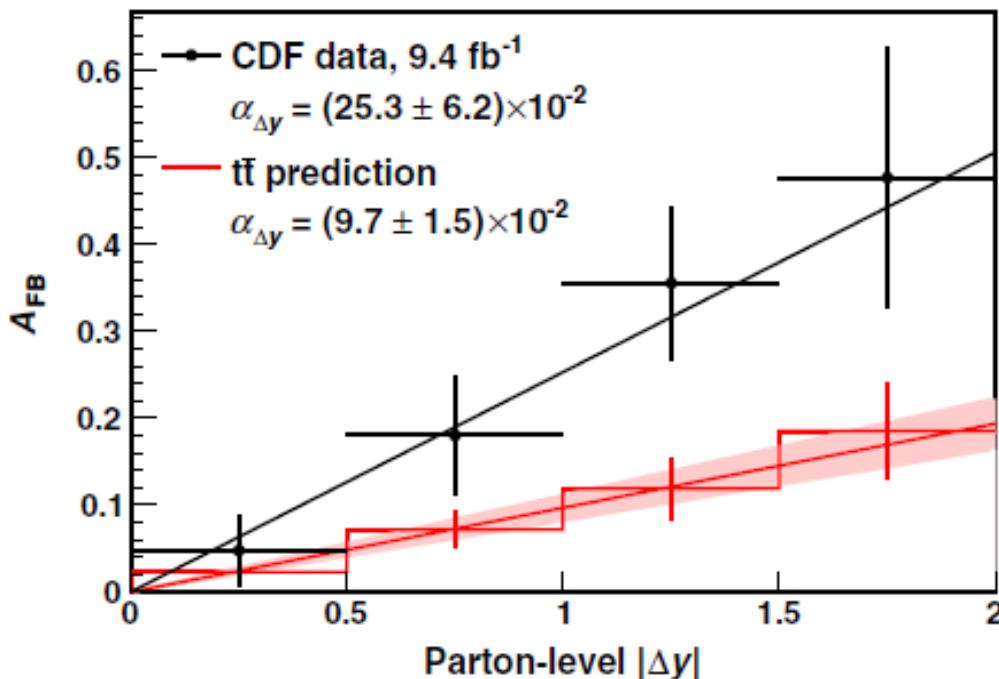
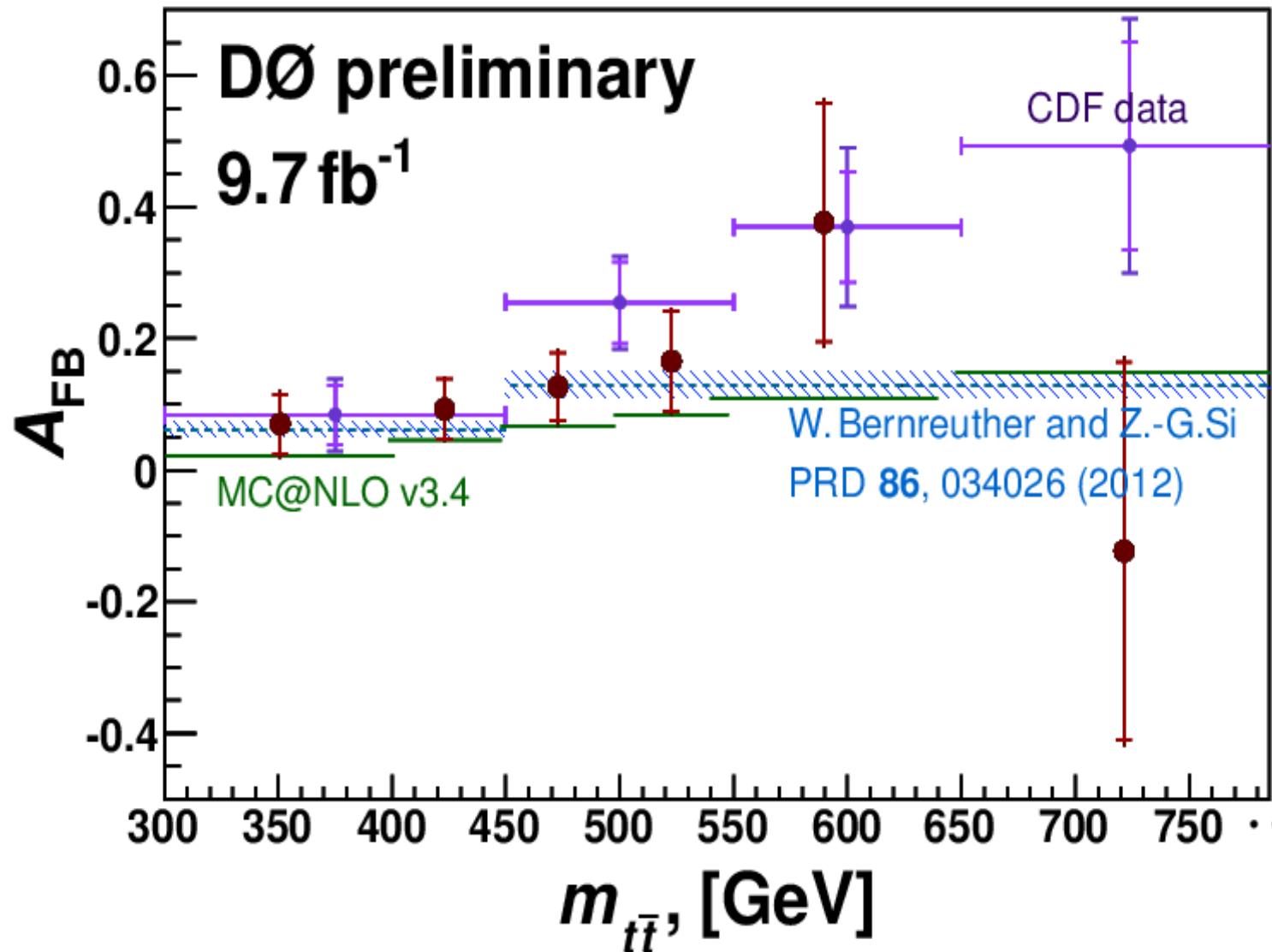


FIG. 3 (color online). Absolute contributions of the Legendre moments to the  $A_{FB}$ , with theory predictions overlaid. The lines and symbols are the same as in Fig. 2. The inset shows the 1-, 2-, and 3-standard-deviation uncertainty ellipses.

# $t\bar{t}$ forward-backward asymmetry



D0 Conf note 6425





# $t\bar{t}$ forward-backward asymmetry



→ CDF Results:

PRD 87, 092002 (2013)

TABLE V. Systematic uncertainties on the parton-level  $A_{FB}$  measurement.

Source	Uncertainty
Background shape	0.018
Background normalization	0.013
Parton shower	0.010
Jet energy scale	0.007
Initial- and final-state radiation	0.005
Correction procedure	0.004
Color reconnection	0.001
Parton-distribution functions	0.001
Total systematic uncertainty	0.026
Statistical uncertainty	0.039
Total uncertainty	0.047

→ D0 results

D0 Conf note 6425

Source	Systematic uncertainties in absolute %		
	Reco. level inclusive	Production level inclusive	2D
Background model	+0.7/-0.8	1.0	1.1–2.8
Signal model	< 0.1	0.5	0.8–5.2
Unfolding	N/A	0.5	0.9–1.9
PDFs and pileup	0.3	0.4	0.5–2.9
Detector model	+0.1/-0.3	0.3	0.4–3.3
Sample composition	< 0.1	< 0.1	< 0.1
Total	+0.8/-0.9	1.3	2.1–7.5



# Lepton based asymmetry

PRD 88, 072003 (2013)

## I+jets, single-lepton asymmetry

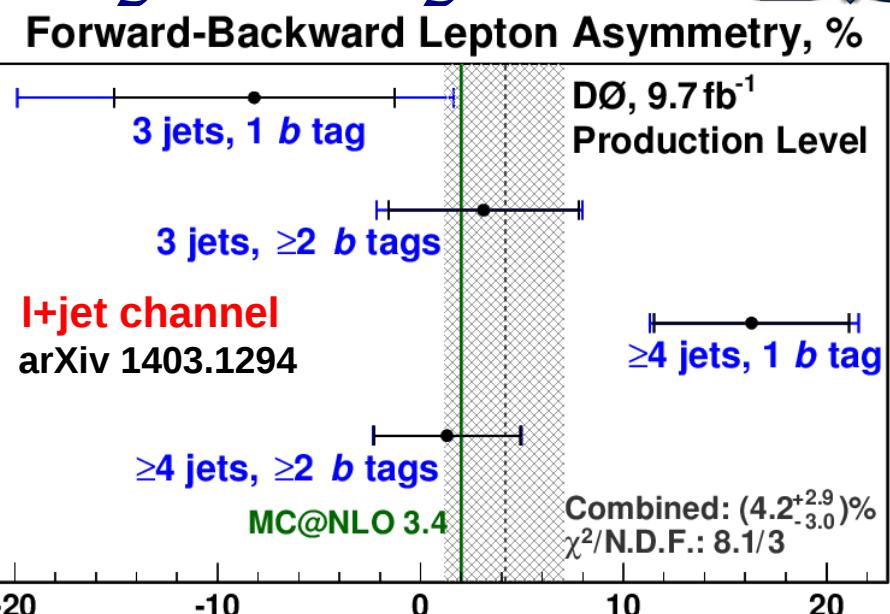
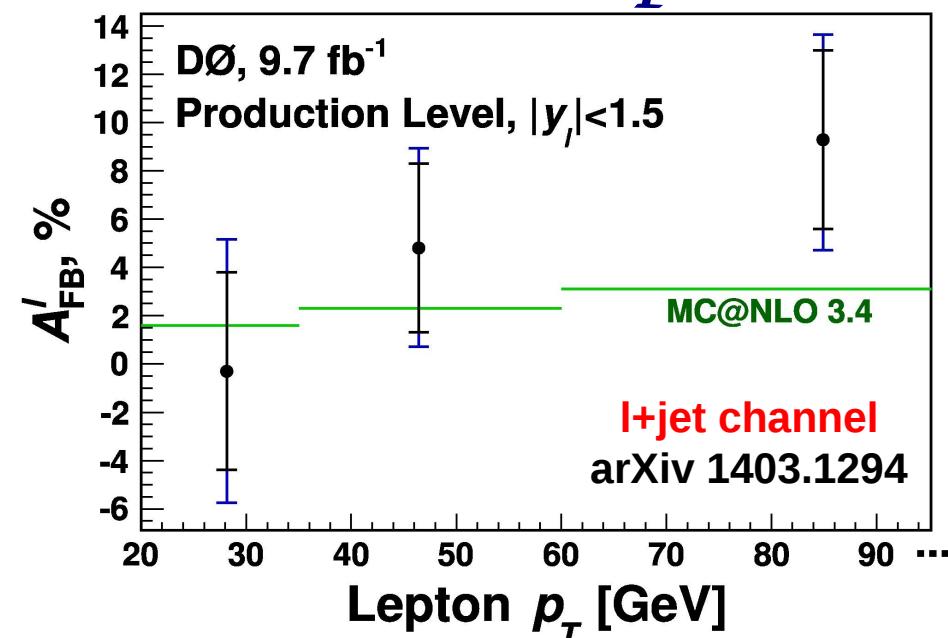
Source of uncertainty	Value
Backgrounds	0.015
Recoil modeling	+0.013 -0.000
Color reconnection	0.0067
Parton showering	0.0027
Parton distribution functions	0.0025
Jet-energy scales	0.0022
Initial- and final-state radiation	0.0018
Total systematic	+0.022 -0.017
Data sample size	0.024
Total uncertainty	+0.032 -0.029

CDF note 11035

## single-lepton asymmetry I+jets + dilepton combination

CDF Run II Preliminary			
Source of uncertainty	L+J ( $9.4\text{fb}^{-1}$ )	DIL ( $9.1\text{fb}^{-1}$ )	Correlation
Backgrounds	0.015	0.029	0
Recoil modeling (Asymmetric modeling)	+0.013 -0.000	0.006	1
Symmetric modeling	-	0.001	
Color reconnection	0.0067	-	
Parton showering	0.0027	-	
PDF	0.0025	-	
JES	0.0022	0.004	1
IFSR	0.0018	-	
Total systematic	+0.022 -0.017	0.030	
Statistics	0.024	0.052	0
Total uncertainty	+0.032 -0.029	0.060	

# Lepton based asymmetry



**dilepton channel (PRD 88, 112002 (2013))**

